Classification of Power Density Spectrum Features and Estimation of the Delta-Invariant Value for the Z Source GX 340+0

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ABSTRACT

We present a theoretical analysis of *Rossi X-ray Timing Explorer* data of Z source GX 340+0 obtained by Jonker et al. In the frameworks of the recently formulated the transition layer model the $\delta-$angle is an angle between the neutron star (NS) magnetospheric axis and the disk (presumably NS rotational) axis. We determine the angle $\delta = 6^o.3 \pm 0.^o3$ which is a combination of the simultaneously observed kHz QPO and HBO frequencies. While these three frequencies change by a factor of three or more their $\delta-$combination stays almost constant. GX 340+0 is the fourth source (in addition to 4U 0614+09, Sco X-1 and 4U 1702-42) for which δ has been determined. With at most one (constrained) parameter we make a complete classification of six observed power spectral features, including the two kHz frequencies, the first and second harmonics of the HBO frequency, low-frequency noise component and break frequencies. We demonstrate that a new component discovered by Jonker et al. in the GX 340+0 power spectrum is related to the viscous frequency branch which has been, in fact reported earlier in 4U 1728-34 by Ford and van der Klis (1998). Finally, we re-classify several previously misidentified features in the power spectrum.

Subject headings: accretion, accretion disks—diffusion—stars:individual (GX 340+0, 4U 0614+09, 4U 1728-34, Sco X-1, 4U 1702-42)—stars:neutron— X-ray:star—waves

1. Introduction

This *Letter* contains the classification of power spectral features in GX 340+0 and a determination of the $\delta-$invariant using observational data from Jonker et al. (2000). Psaltis, Belloni & van der Klis (1999) discussed many similarities and correlations between the QPO frequencies in atoll sources, Z-sources and black hole candidates, which may be related to the similar phenomena and physical processes occurring in all of these systems. In addition, Wijnands & van der Klis (1999) found that the break frequency of the broken power law which describes the power spectrum

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correlates well with the frequencies of the peaked noise components observed in atoll sources and black hole candidates. Titarchuk & Osherovich (1999; hereafter TO99) attempted to classify QPO frequencies using the basic properties of accretion flow around compact objects. The first property is an adjustment of the Keplerian flow in the disk to the sub-Keplerian inner boundary condition (Titarchuk, Lapidus & Muslimov 1998, hereafter TLM98), which is a common phenomenon for neutron star (NS) and black hole candidate systems. In this respect all correlations between the break frequencies ν_b and low QPO frequencies ν_V should be similar in both types of system because they are related to the diffusion and oscillation time scales in the transition region between the Keplerian flow and the rotational inner boundary (either the NS surface or the inner edge of the accretion flow in BH systems). Later the predicted correlation was confirmed by Ford & van der Klis (1998) who analyzed RXTE data from 4U 1728-32. Furthermore, in TO99 the authors demonstrated that ν_b and ν_V are related through the power law $\nu_b \propto \nu_V^{1.6}$ which fits to the data in most BH and NS systems (Wijnands & van der Klis, 1999).

The second property is an effect of the sub-Keplerian rotating magnetosphere located above the disk. Osherovich & Titarchuk (1999a, hereafter OT99a) suggested that the radial oscillations of the fluid element bounced from the disk shock region (presumably at the adjustment radius) would be seen as two independent oscillations in the radial and the vertical directions due to the presence of Coriolis force in the magnetospheric rotational frame of reference. The observed evolution of two kHz peaks allows one to infer the profile of the differentially rotated magnetosphere and then to verify it using the observed correlation of the horizontal branch quasi-periodic oscillations (HBO) frequencies with the low kHz peak.

In a black hole system the corona above the disk should also rotate with less than Keplerian velocity. When oscillating fluid elements of the disk are thrown to the corona, these oscillators would be under the influence of the Coriolis force which leads to the same rotational splitting effect (OT99a) seen in the NS systems. The main QPO Keplerian frequency would be split into two frequencies, the hybrid and low branch related to the radial and vertical oscillations respectively in the rotational frame of references.

The recent discovery of a 450 Hz QPO (Strohmayer 2001) in addition to the previously reported 18 and 300 Hz (Remmilard 1999) in GRO J1655-40 provides additional support for the rotational splitting effect.

There are three other QPO models in the literature. The first one is the beat frequency model suggested by Alpar & Shaham (1985), and recently modified as a sonic-point beat frequency model by Miller, Lamb & Psaltis (1998). The second is the relativistic precession model proposed by Stella & Vietri (1998, 1999). The third is the inner accretion disk model promoted by Psaltis & Norman (2000). All observational arguments for these models and their problems are discussed in detail by Wu (2001) where these models are also compared with the transition layer model (TLM) (TLM98, TO99-OT99a). We do not go into the details of this comparison in this Letter but we do give more arguments for TLM in terms of the new QPO data for GX 340+0 (Jonker et al. 2000,

here after J00).

Precise simultaneous measurements of the frequencies of the two kHz QPOs and HBO harmonics in a wide frequency range for GX 340+0 (J00) give us an opportunity to derive the $\delta-$invariant. In Osherovich & Titarchuk (1999, hereafter OT99b), the authors demonstrated for the source 4U 1702-42 that the inferred angle δ, (see Eq 2, 5 in OT99b)

$$\delta = \arcsin\left[(\nu_h^2 - \nu_{\rm K}^2)^{-1/2}(\nu_L\nu_h/\nu_{\rm K})\right] \tag{1}$$

depends only on *observed frequencies:* the low and high kHz QPO peaks $\nu_{\rm K}$, ν_h and the HBO (the low branch) peak ν_L. It stays the same ($3.9^o \pm 0.2^o$) over significant range of $\nu_{\rm K}$ (650-900 Hz). Using a series of observations where ν_h, $\nu_{\rm K}$, ν_L are detected simultaneously [van der Klis et al. 1997; Markwardt, Strohmayer & Swank 1999; van Straaten et al. 2000; J00)] we check that the angle δ is a true invariant for four specific sources: Sco X-1, 4U 1702-42, 4U 0614+09 and GX 340+0 (see §2). We present the magnetospheric rotational profile for GX 340+0 inferred from J00 data in §3. Using this profile and the δ value we will reproduce the theoretical dependence of the low branch on the low kHz frequency in §4 and compare it with the J00 observations.

According to the TLM, also known as "two-oscillator model" all frequencies (namely ν_h, ν_L, ν_b and ν_V) have specific dependences on $\nu_{\rm K}$.

The comprehensive summary of the TML model and its successes to date is present in Titarchuk & Osherovich (2000a)

In §5 we offer the full classification of the QPO frequencies containing six branches which fit to the data with at most one (constrained) parameter. Discussion and summary follow in the last section.

2. $\delta-$Invariant and Verification of Transition Layer Model

We have used the frequencies measured for sources GX 340+0, 4U 0614+09, Sco X-1 and 4U 1702-42 where the low and high kHz QPO peaks $\nu_{\rm K}$ and ν_h and HBO frequencies ν_L are measured simultaneously. The resulting values of δ calculated from Eq. (1) are shown in Figure 1. Indeed, for each of these sources, the $\delta-$values show little variation with $\nu_{\rm K}$, ν_h, ν_L. They are $3^o.9 \pm 0^o.2$, $5^o.5 \pm 0^o.5$, $15^o.3 \pm 0^o.5$, for 4U 1702-42, Sco X-1 and 4U 0614+09 respectively. The angle δ obtained for the source GX 340+0 is $6^o.3 \pm 0^o.3$ and is similar to the values obtained for Sco X-1 and 4U 1702-42. The existence of the $\delta-$invariant predicted by the TLM [OT99b, Titarchuk & Osherovich (2000b here after TO00)] is a challenge for any other QPO model. It is important to note that *all frequencies included in this $\delta-$relation are observed frequencies and thus the relation Eq. (1) is a model independent invariant.* It is worth pointing out once again that the *delta*$-$angle varies from source to source.

In fact, Wu (2001) confirms the existence of the delta-invariant for three more sources – Cyg

X-2, GX 17+2 and GX 5-1, using the RXTE observational data obtained by Psaltis et al. (1999), Wijnands et al. (1998a,b, 1997). For all these sources the $\delta-$angle is about 6^o which is very close to that obtained for Sco X-1 and GX 340+0. The accuracy of $\delta-$ determination is of order 5%.

3. Inferred Rotational Frequency Profile of the NS Magnetosphere in GX 340+0

From the observed kHz frequencies (J00, Table 3), ν_h and $\nu_{\rm K}$, the profile of $\nu_{mag} = \Omega(\nu_K)/2\pi$ has been calculated according to

$$\nu_h = [\nu_{\rm K}^2 + 4(\Omega/2\pi)^2]^{1/2}, \tag{2}$$

and modeled using the theoretically inferred magnetic multipole structure of a differentially rotating magnetosphere (OT99a)

$$\nu_{mag} = C_0 + C_1\nu_{\rm K}^{4/3} + C_2\nu_{\rm K}^{8/3} + C_3\nu_{\rm K}^4 \tag{3}$$

where $C_2 = 2(C_1C_3)^{1/2}$. The constants $C_0 \equiv \nu_{mag}^0 = 330$ Hz, $C_1 = -9.72\times10^{-2}$ Hz$^{-1/3}$, $C_2 = 5.34\times10^{-5}$ Hz$^{-5/3}$ and $C_3 = -7.32\times10^{-9}$ Hz^{-3} have been obtained by a least-squares fit with $\chi^2 = 15.8/12$. The ν_{mag} profile for GX 340+0 is very similar to those of 4U 1608-52, and Sco X-1 (see OT99a, Figs. 1-2).

4. Low Branch Frequency vs kHz QPO Frequency

The GX 340+0 data of J00 allows one to check the prediction of the model for the low branch frequency ν_L. Taking the profile of $\nu_{mag}(\nu_{\rm K})$, (Eq. 3), we plot ν_L in Figure 2. Fixing $\delta = 6^o.3$, we find that our plot for ν_L and $2\nu_L$, calculated according to formula (OT99a, Eq. 9)

$$\nu_L = 2\nu_{mag}(\nu_{\rm K}/\nu_h)\sin\delta, \tag{4}$$

fits the data for the observed frequencies of (20-40) Hz and (40-80) Hz respectively. There are three observational points in Figure 2 (square points with error bars) which we interpret as the second harmonics $2\nu_L$. The first harmonics ν_L for these frequencies are not observed by J00 and they are obtained using $2\nu_L$ and presented as squares without error bars. The error bars of the observational points shown by circle marks are less than the mark size in most cases. It is worth noting that the observational points follow the theoretically predicted curve, which shows the signs of saturation at high $\nu_{\rm K}$. The same type of behavior of ν_L vs $\nu_{\rm K}$ is also seen in the Sco X-1 data.

5. Break and Viscous frequencies vs kHz QPO Frequency Correlations

Further tests of the TLM can be done using a comparison of the observed correlations of break and viscous QPO frequencies vs kHz QPO frequencies (J00) with the theoretical depen-

dences derived in TLM98 and TO99. In Figure 3 (the classification plot), we present the theoretical curves calculated using Eqs. (9, 12-13) in TO99 using the dimensionless parameter $a_{\rm K} = m(x_0/3)^{3/2}(\nu_0/363\ {\rm Hz})$ where ν_0 is the neutron star (NS) spin, m is the NS mass in the solar masses, x_0 is the NS radius in units of Schwarzchild radii. In TO00 (Eq. 4) we approximate the solution of Eq (9) of TO99 by a polynomial $\nu_b = C_b P_4(\nu_{\rm K})$ for $a_{\rm K} = 1.03$ and $\nu_{0,363} = \nu_0/363\ {\rm Hz} = 1$. The normalization of the theoretical curve is controlled by the constant C_b (TO00) which reflects the properties of the specific source. For instance, for 4U 1728-34 the observed frequencies are fitted by the curve (TO99) for which the constant $C_b = 1$ and $R_0 = 10$ km for 1.4 solar masses (see TO00, Eq. 2). It should be pointed out that the NS spin for 4U 1728-34 is known to be $\nu_0 = 363$ Hz. For GX 340+0 we fit the data points by curves with the parameter $\nu_0 = 363$ Hz for which the corresponding constant $C_b = 7.6$. For the source GX 340+0 we found the Lebesgue's measure (for a definition, see Titarchuk, Osherovich & Kuznetsov 1999, hereafter TOK) is 16% for $a_{\rm K} = 1.03$. In fact, the theoretical curves are functions of two parameters, $a_{\rm K}$ and ν_0, and for (a given) $\nu_{0,363}$ that curve with $\nu_{0,363} = 1$ can be obtained by scaling the argument (see TO00).

According to solutions presented in TO99 and TOK, the break frequency ν_b correlates with the low Lorentzian frequency ν_V (which we interpreted as a viscous frequency in the TL model) through the power law relation

$$\nu_b \propto \nu_V^{1.61}. \tag{5}$$

Using the data of Wijnands & van der Klis (1999) it was confirmed in TOK that approximately the same index is valid for most NS and BH objects. We have also found that the observed correlation of ν_b vs ν_V in GX 340+0 is well described by the same power law dependence (Eq. 5) but with a proportionality coefficient 0.08 (which is twice more than that for 4U 1728-34). The dependence of ν_V vs $\nu_{\rm K}$ is shown in Figure 3 by the red curve. To fit the theoretical curve to the data we use only those data points which were specified by J00 as the new discovered frequencies. They pointed out that these frequencies well close to half that of the HBO. However looking at the classification in Figure 3 we argue that these power spectral features are the same low noise component frequencies – in our terms, ν_V– that were found by Ford and van der Klis (1998) in 4U 1728-34 and by TOK in Sco X-1. Furthermore, we have found that at least two power spectra features which were identified by J00 as the break frequencies also belong to the viscous branch. The appropriate points are denoted by triangle marks in Fig. 3.

The dependences of ν_b and ν_V on $\nu_{\rm K}$ allow us to retrieve information regarding the turbulent scale $l_{\rm fp}$, the sonic velocity v_s, the magnetic field strength and structure in the transition layer. We discuss these issues in detail in Titarchuk, Bradshaw & Wood (2001).

Wu (2001) uses the $\alpha-$prescription – i.e. $\alpha \sim (l_{\rm fp}v_t)/(v_s H)$, where H is a half-thickness of the disk – to specify the absolute value of the viscous frequency ν_V. However we argue that the introduction of one more free parameter (α) in TL model is not necessary and furthermore it leads to very small values of kinematic viscosity, $\mu_{\rm kin} = v_t l_{\rm fp}/3$. One may conclude using Wu's best-fit parameters of $\alpha(H/R)^2 \sim 10^{-3}$ that $v_t l_{\rm fp}$ is at least two orders of magnitude less than $v_r L$. On the other hand, the Reynold's number γ is tightly constrained by the observed absolute values of kHz

frequencies (TLM98, Fig. 3) and one can find that $v_t l_{\rm fp} > L v_r/4$. In TLM98 authors have already realized this problem with the $\alpha-$ prescription and therefore they have not used it in the model.

6. Discussion and Conclusions

In this *Letter* we have further verified predictions of the transition layer (TL) model for four sources by presenting our analysis of Jonker et al.'s GX 340+0 data. Furthermore we demonstrate that the right classification of the power spectra features allows us to shed light on their nature and origin. The unifying characteristic of TLM is that all QPO features are natural and necessary consequence of the adjustment of Keplerian disk to the sub-Keplerian rotation of the neutron star. In the transition layer the interaction of the two oscillators may occur because they share the common boundary at the outer edge of the transition layer. In this case a strong dependence is supposed to exist between all frequencies in the TLM and the fundamental Keplerian frequency $\nu_{\rm K}$ at the TL outer edge. In our model, assuming high electric conductivity, we describe the frequency of the differential rotation of the magnetosphere ν_{mag}. We also assume that the NS magnetic field has a discontinuity in the equatorial plane similar to the discontinuity of the field in the equatorial plane of the solar corona and related current sheet in the heliosphere as described in the model of Osherovich, Tzur and Gliner (1984). Both the current sheet and differential rotation are observed elements of solar corona and heliosphere (e.g. Hoeksema & Scherrer 1987, Burlaga 1995).

The TLM model reveals the physical nature of the low branch (HBO) oscillation frequency as a low branch of the Keplerian oscillator under the influence of the Coriolis force. The angle δ as a global parameter describes the inclination of the magnetospheric equator to the equatorial plane of the disk. Measured locally for different radial distances (therefore different ν_K), δ may vary considerably if the observed oscillations do not correspond to the predicted low Keplerian branch. The angle δ is calculated using the observed frequencies only. The constancy of δ shown in Figure 1 argues in favor of our model. Thus, if a similar rotational splitting effect occurs in BH systems, are the needed frequency trio simultaneously observed: a pair of high frequencies of order 200-300 Hz (for black hole with mass of 7-10), and a low frequency close to 20 Hz? Strohmayer (2001) reports precisely this case for BH candidate GRO J1655-40. He simultaneously observed three frequencies, 450, 300 and 18 Hz.

If we assume the rotational splitting paradigm as an origin for these three frequencies, we can estimate the rotational frequency of the corona-configuration above the disk $\Omega/2\pi = 167.7$ Hz using the hybrid relation (OT99, Eq. 7) for $\nu_h = 450$ Hz and $\nu_{\rm K} = 300$ Hz. Furthermore, if we assume that the corona configuration rigidly rotates with the black hole, we can estimate the BH dimensionless angular momentum $a = cJ/GM^2 = \Omega GM/c^3 = 3.6 \times 10^{-2}$. We have also assumed a BH mass of about seven solar masses. The low 18 Hz frequency can be interpreted as the low branch QPO if $\delta = 4.6^o$ (see Eq. 1), which is a typical for NS systems (see Fig. 1).

Strohmayer (2001) argues that the GRO J1655-40 QPO data, with $0.4 < a < 0.6$, could

account for the higher frequency, 450 Hz, when identified with the radial epicyclic frequency within relativistic disk models (see e.g. Stella, Vietri & Morsink 1999; Psaltis & Norman 2000; Markovich 2000). He also suggests that the 300 Hz QPO is associated with lower kHz QPOs in neutron stars (*c.f.* OT99 and Psaltis et al 1999). However, if this parallel between NS and BH systems assumes that the higher frequency QPO twin frequency is due to General relativity (GR) effects, the question arises of how this GR model works for NS systems when kHz QPO frequencies of 400-500 H (corresponding to 10-12 Schwarzschild radii where GR effects are negligible) are observed. Such QPOs, along with higher kHz frequencies, are seen very often in NS systems (see Fig. 4). One may conclude that the association between QPOs in NS and BHC along with their interpretation within the GR model is somewhat problematic.

The observed correlations of the viscous and break frequencies versus kHz QPO frequencies allow us to retrieve information about the NS spin. We found that for GX 340+0 as well as for Sco X-1 the NS spin should be close to 360 Hz which is similar to that measured directly in 4U 1728-34 (Strohmayer et al. 1996). On the other hand there is an indication (TO00) that the NS spin in 4U 0614+09 can be as high as 700 Hz or more.

The authors acknowledge discussions with Joe Fainberg, Kent Wood and Reba Bandyopadhyay. We are grateful to Peter Jonker for use of his data. We are also grateful to the referee for a thorough analysis of the paper content and constructive suggestions

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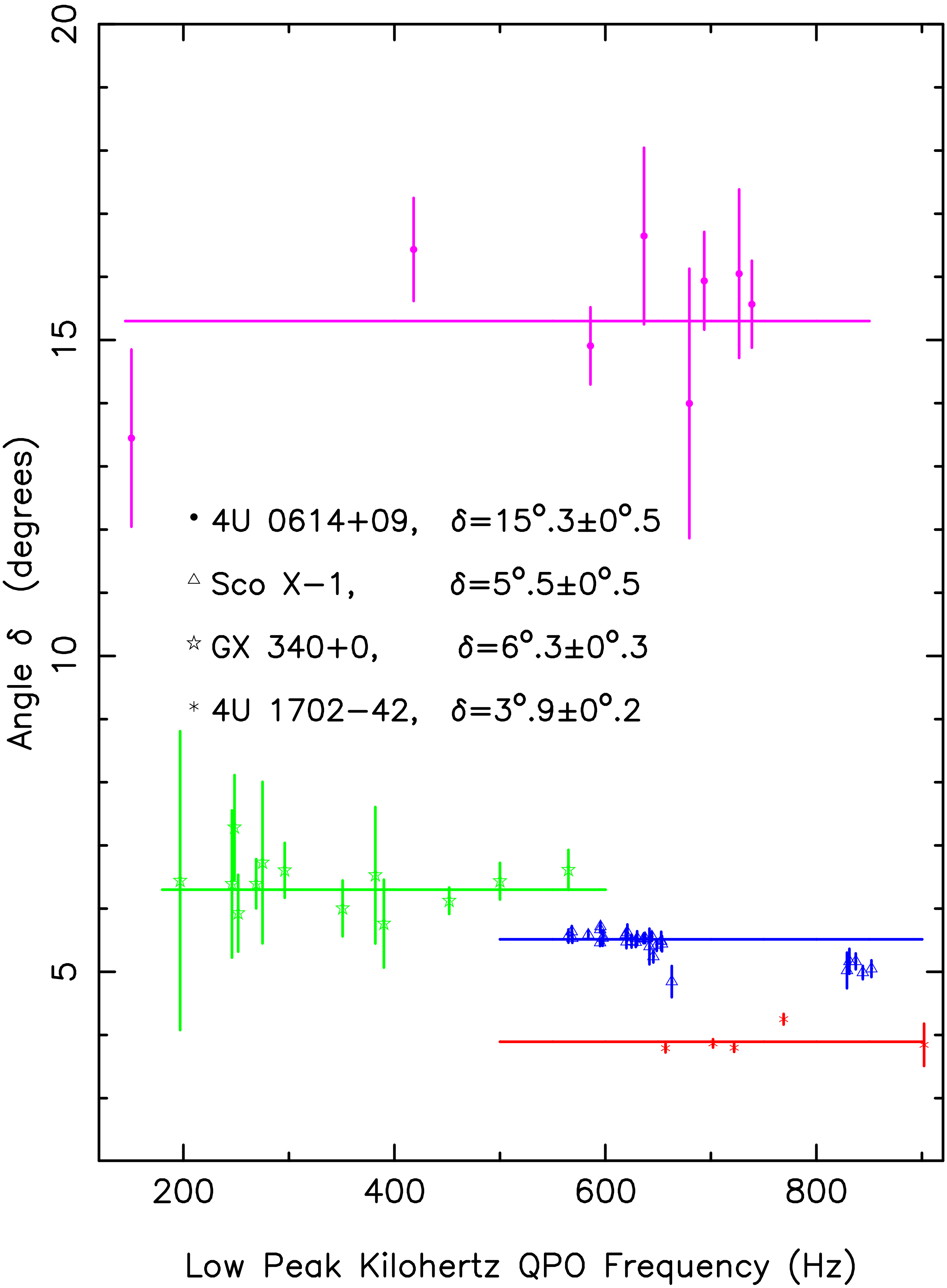
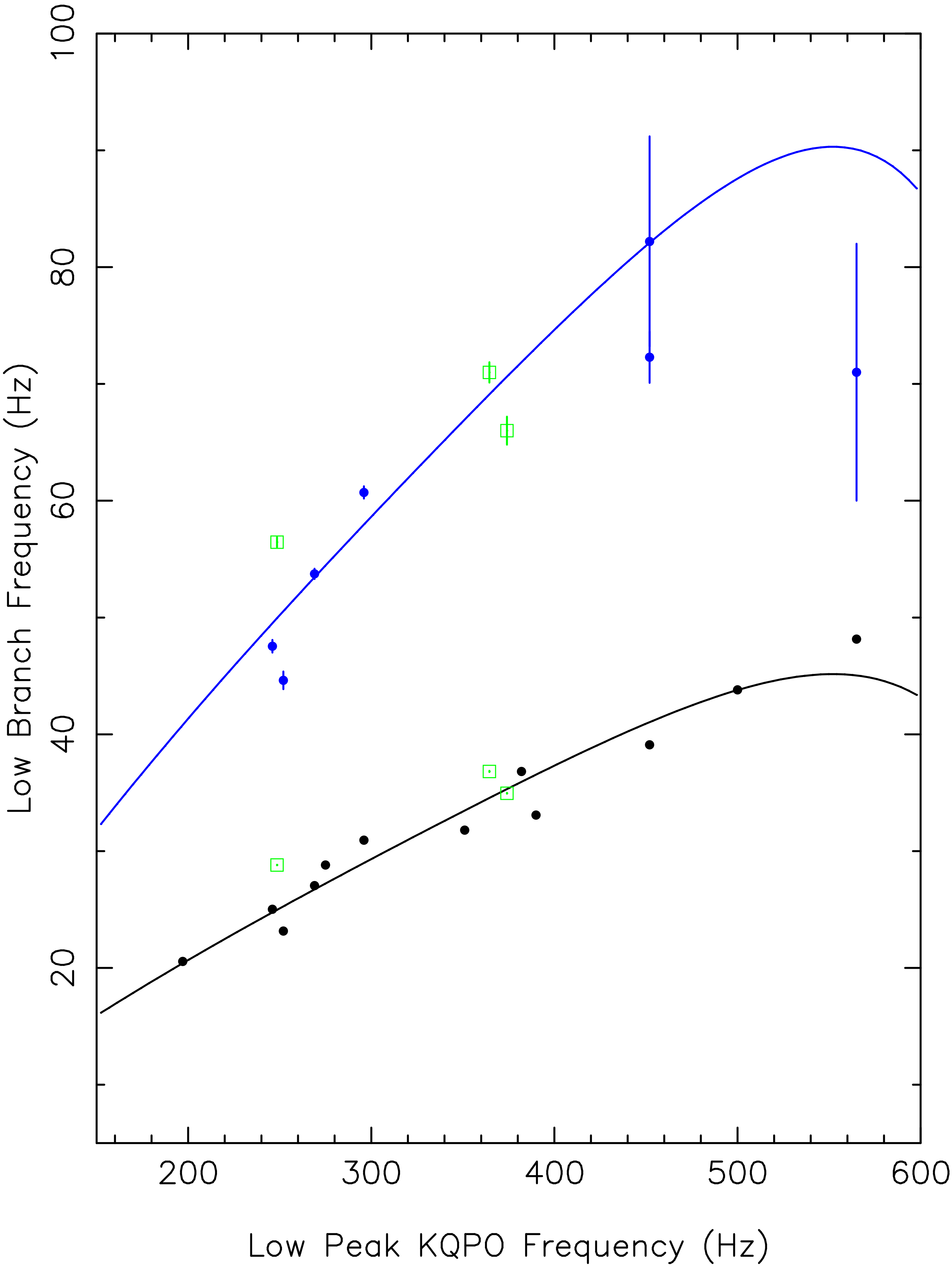
Fig. 1.— $\delta-$invariant. Inferred angles δ between the rotational axis of magnetosphere and the normal to the plane of Keplerian oscillations as a function of low peak kHz QPO frequency for four sources: GX 340+0 (green), 4U 0614+09 (magenta), Sco X-1 (blue), and 4U 1702-42 (red) . The $\delta-$invariant (eq.[1]) is calculated using the observational frequencies ν_h, $\nu_{\rm K}$ and ν_L only.

Fig. 2.— HBO frequency vs low kHz QPO frequency for GX 340+0 (Jonker et al. 2000). The solid line is the theoretical dependence of the low branch oscillation frequencies (black) and the second harmonics (blue) on the Keplerian frequency, calculated using multipole expansion of the rotational frequency. The points for the first harmonic of the low branch (green squares) are obtained by dividing by 2 the observational frequencies of the second harmonic (which are the green squares with error bars).

Fig. 3.— Classification of QPOs in the Z source GX 340+0. Solid lines are the theoretical curves: Blue for the Upper hybrid frequency branch, magenta for the second harmonic of the low branch, blue for the first harmonic of the low branch, red for the viscous branch and black for the break frequency branch. The points with squares for the first harmonic of the low branch are obtained by dividing by 2 the observational frequencies of the second harmonic (blue squares). The observational points with black triangles are identified by Jonker et al. (2000) as break frequencies. The theoretical curves for viscous and break frequencies branches are constructed using the first six viscous frequency points (red asterisks) and the first seven break frequency points (black triangles) respectively.



• 4U 0614+09, δ=15°.3±0°.5
△ Sco X−1, δ=5°.5±0°.5
☆ GX 340+0, δ=6°.3±0°.3
* 4U 1702−42, δ=3°.9±0°.2
Angle δ (degrees)
Low Peak Kilohertz QPO Frequency (Hz)
5
10
15
20
200
400
600
800



100
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20
Low Branch Frequency (Hz)
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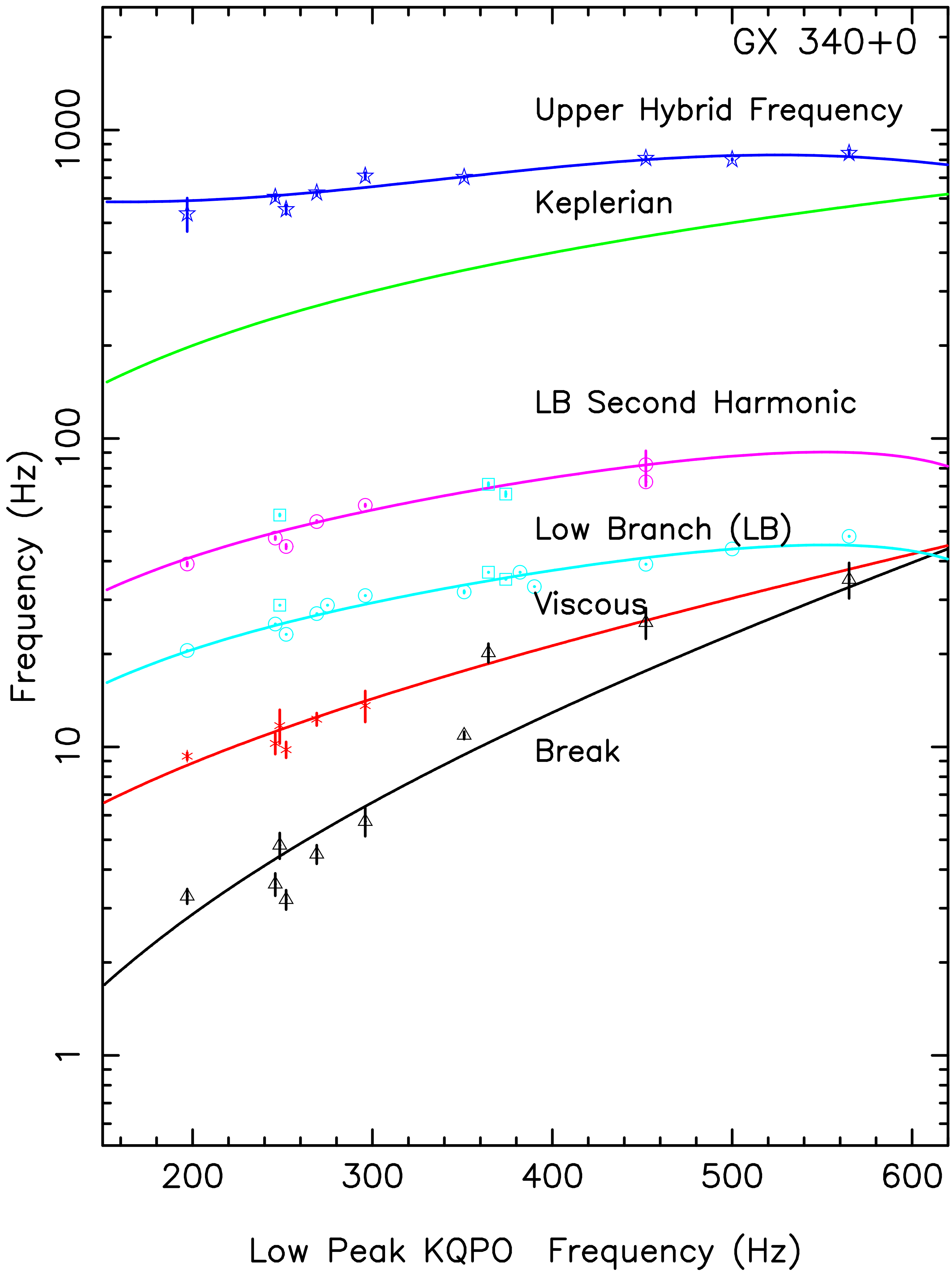
Low Peak KQPO Frequency (Hz)


GX 340+0
Upper Hybrid Frequency
Keplerian
LB Second Harmonic
Low Branch (LB)
Viscous
Break
Frequency (Hz)
Low Peak KQPO Frequency (Hz)
1000
100
10
1
200
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